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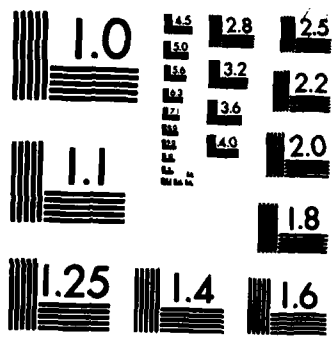
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THE PROCESS BY WHICH DOUBLE BASE PROPELLANTS WITH
EMBEDDED CONTINUOUS WIRES ARE FABRICATED BY
USE OF THE SCREW EXTRUDER

by

Yu Li Xie and Xi You Yang



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The Process by which Double Base Propellants with Embedded Continuous Wires are Fabricated by use of the Screw Extruder

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Abstract

This paper describes a process by which the screw extruder is used to produce double base propellant grains embedded with continuous metal wires. By using the fabrication process developed during this research, it is not only possible to satisfy a full range of design requirements, but also to produce double base propellant grains with continuous wires that are embedded without distortion. These double base propellant grains with embedded continuous wires are capable of stable combustion in standard 50mm diameter rocket motors. The axial rate of combustion of end-firing grains with six 0.13mm diameter wires is five times that of the propellant matrices themselves (without embedded wires).

Further, the present report describes the experimental apparatus by which a screw extractor was used to produce the double base propellant grains with embedded continuous wires. The various factors which influence the quality of the propellant grains thus produced were also investigated. Additional topics studied here include the construction of the propellant matrix, type and diameter of wire, choice of surface coating, and the method by which wire-embedded grains may be produced so as to satisfy the design demands of given rocket thrust requirements.

1. Introduction

The embedding of metal wires is an effective method for increasing the axial combustion rate of solid propellants and the surface area of combustion in end-surface propellants. As a result of our experiments, the embedding of continuous metal wires into propellants has several advantages, as follows: (1) end-surface propellant design is simple; (2) combustion time is long; (3) mechanical properties are good; (4) density of charge is high; and (5) there is no corrosion-related combustion. In addition, even in small-diameter end-surface combustion configurations great amounts of thrust are attained. Also, it is possible to regulate the thrust of the rocket motor through changes in the type and gauge of wire and through surface coatings. In particular, this method of wire embedding is useful in the attainment of double thrust from single-charge propellants.

Studies on the embedding of wires into injection-type grains of composite propellants have been undertaken in other countries from 1960 onward, and the effective use of propellants with embedded wires has already been accomplished.^{1,2} Both long and short wire embedding schema have been used. In order to increase the radial combustion rate of the propellant grains,

electro-magnetically charged wires have been introduced into propellant slurries and arranged in a radial configuration by the application of an electrical charge.

In recent years, researches on the embedding of wires in propellant grains in propellant grains have also been undertaken in our country. It is already possible to embed wires in injection-type grains of composite propellant and extruded double base propellant grains.

It is believed that the method of embedding continuous wires in screw-extruded double base propellant grains is a new theme in the field of research into ammunition manufacturing methods. This research is not only related to the question of the design of the extruded body, but also to the questions of the rheology of the propellant mixture during preparation and its strength analysis during the process of hardening.

Through a large number of experiments, we learned how to simply embed wires into double base propellant grains through the process of screw extrusion. It is possible to create a grain with a diameter of 45 mm and six embedded wires by using an 80 mm diameter screw extruder (see diagram 1).

X-ray photography was used to verify that the continuous wires embedded in the propellant grains were both straight and in the desired configuration. (See diagram 2.) Furthermore, when the extruded grains are fired from both directions in a standard 50 mm rocket motor, the result is stable combustion. On the basis of power-time curves we verified that, when the conditions of rocket motor combustion with propellants embedded with six continuous silver wires are identical, the combustion vector of the motor is identical to that of the wire-embedded propellant. That is, we verified that propellants with identical combustion properties could be prepared consistently.

We discovered that the improvement of the extrusion process of creating double base propellants with continuous embedded wires has widened the range of usefulness of double base propellants. In addition, this type of propellant is now realized to be applicable to the currently developing process of eliciting dual-stage thrust from simple combustion chambers.

2. Construction methods and equipment

2.1 Determination of the position of the embedded continuous wires during the formation of the screw extrusion body

Consideration of the flow properties of the propellant mix during the process of screw extrusion fabrication indicates that the embedding of continuous wires into the expansion stage of the developing extrusion body is not advantageous. The reason for this is that the propellant mix expands as its rate of flow decreases when entering the expansion stage. If the continuous wires are embedded at this point they are easily bent, so that their position with the grain is less easily fixed. The impact of the rocket's thrust is applied not only in the axial direction against the propellant mix in the contraction stage, but also radially against the container walls in the same stage. Because of the gradual decrease in the cross-section surface area of the cone that describes the propellant mix flow, when propellant mix is added at a steady rate it effectively forces ever

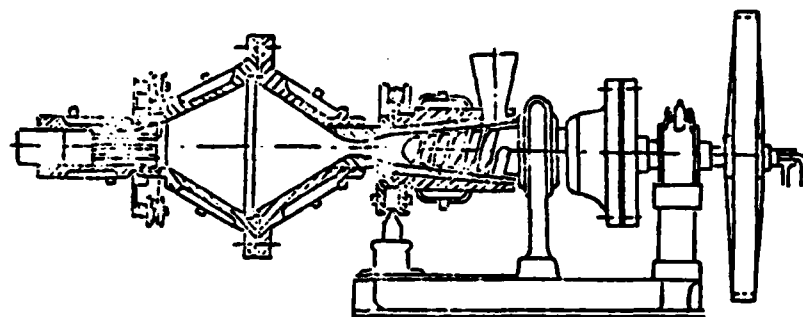


Diagram 1: Screw extrusion apparatus for the embedding of continuous metal wires

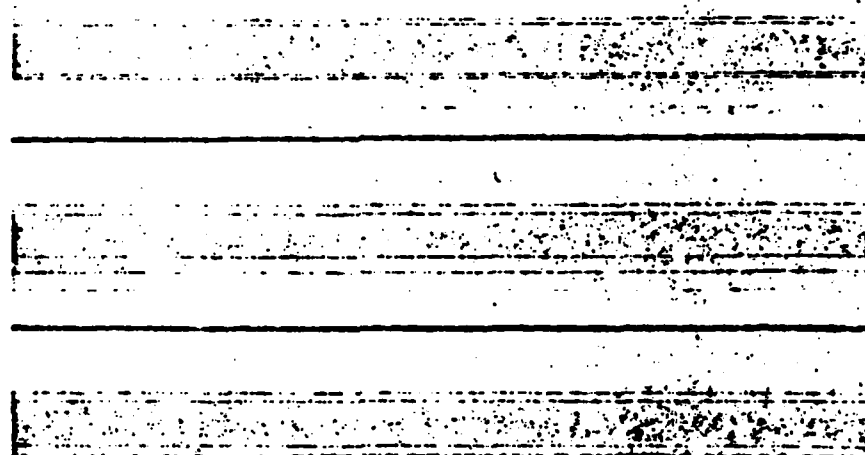


Diagram 2-1: X-ray photograph of 45mm diameter propellant grain with six embedded silver wires

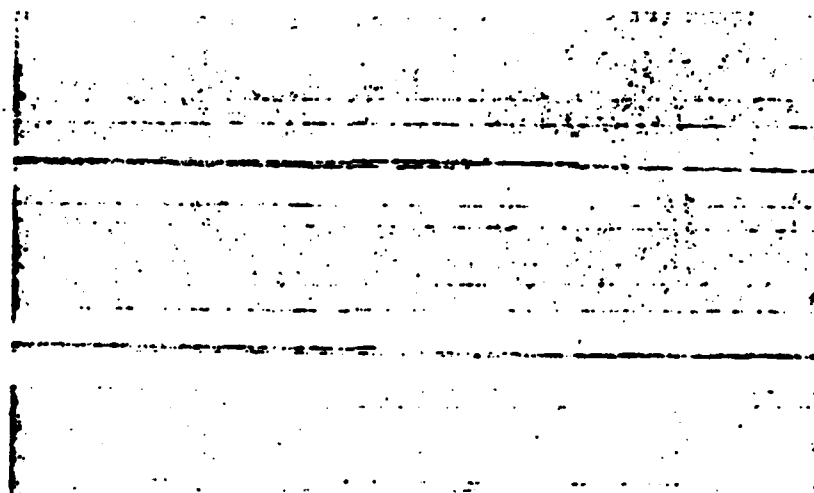


Diagram 2-2: X-ray photograph showing distortion of metal wires within a 45mm diameter propellant grain

greater rates of flow. In addition, it is possible that the mix will concentrate in the center. If continuous wires are embedded in the contraction stage, the radial pressure will concentrate itself on the wires and the stability of the placement of the wires within the grain will be difficult to ensure. At the same time, because of changes in the rate of flow of the propellant mix axially, the wires will be subjected to stretching. If this stretching exceeds the specific tensile strength of the wires they will break. Therefore, it is impossible to embed wires in the contraction stage of the propellant grain.

It has been realized as a result of the analysis of the flow of propellant mix that the embedding of continuous wires into the developing extrusion body is the best approach. The reason for this is that the developing extrusion body does not change in end surface area axially. That is, it is because the propellant mix flows evenly in an axial direction within the developing body. When continuous wires are embedded during this process, it is not only possible to ensure their placement in the desired positions, but it is also assured that the wires will not bend and break.

However, because there is no central concentration when propellant mix is flowing within the mold of uniform cross-section area, the wires are difficult to insert. This problem may be solved with an increase in the compression differential and changes in the design of the needle-holding mechanism. It is believed that the embedding of continuous wires in the mold is the best method for the production of wire-embedded propellant grains.

2.2 Experimental devices

The equipment used in these experiments were an 80 mm diameter screw extruder, a 150 mm diameter cone, and a 45 mm diameter mold. A needle-holding device with six model-type needles is attached between the contraction stage of the cone and the mold. After surface treatment of the wires they are passed from the supply spool through the central hole of the needle mechanism and thus into the mold. They are then inserted into the propellant grain with the aid of other needles above them in the mold.

As indicated in diagram 1, in order for the wires to be embedded in the correct positions it is necessary to ensure prior to embedding that the needles are not bent as they are inserted into the propellant grain. Insertion tubes are attached to the mold above the needles and fitted with restraining rings and rubber stoppers. The purpose of these is to increase the power by which embedding into the propellant mix occurs.

If the pressure from the developing grain exceeds the restraining power of the rubber stoppers, then the propellant grain is forced out concurrently with the insertion tubes and restraining rings. Therefore, it is possible to ensure that the wires will be embedded without bending in the propellant grain. By this method it is possible to obtain propellant grains embedded with wires in a fashion that matches production requirements.

3. The various factors affecting the quality of grains with continuous wires embedded through use of screw extrusion

Through a long series of experiments, we have learned that there are many factors which influence the quality of grains having continuous wires embedded through use of screw extrusion. The most important of these are the processed propellant mix, the model, and the types, geometrical configuration, and production conditions of the embedded wires. The detailed explanation of these factors is as follows:

3.1 Influence of the mold

The most important factor bearing on the question of whether or not the propellant grain with its embedded wires can be removed from the mold is the design of the mold itself. The fundamental rule is that the design should make appropriate accommodation for the resistance of the propellant mix during the process of extrusion.

It is necessary that the propellant mix maintain correct conditions of flow during the process of grain extrusion. In addition, the mix must maintain fixed flow conditions as it passes through the mold. If there are inconsistencies in the mold's response to propellant mix resistance, then wave action will probably occur as the mix flows through the mold. When the cross-section area of the mold is constant then the flow will be rapid in locations where resistance is small and, in the opposite case, flow will be slow where resistance is high. When such inconsistencies occur the lengths of the wires coming from the various needles in the mold will differ and the wires themselves will not be straight within the grain. Therefore, a well-designed mold is necessary for the production of propellant grains with embedded wires.

3.2 Influence of the geometric configuration of the mold's needles

There is a very close relationship between the status of the continuous wires, which are embedded within the grain and the length and gauge of the mold's needles used to introduce those wires. If the needles are too short, the wires are easily stretched and broken. If they are too long, the wires are easily bent. After an appropriate length is decided upon, the gauge of the needles then becomes important. If the needles are too small, the wires are easily bent. If they are too large, the wires will not be intimately mated to the propellant mix. In addition, it is necessary to consider the nature of the propellant mix when choosing a needle design. That is, the length of the needles must be chosen with consideration of the firmness of the propellant mix. Because the properties of propellant mixes vary their ability to communicate, the pressure applied by the screw extruder and their conditions of flow while under pressure also vary.

It is also believed that the angle of the mold's contraction stage cone influences the choice of needle length. The smaller that angle, the greater the tolerance available in adjusting needle length. When using SDP-10 propellant mix, the requirements are as follows: the outer diameter of the needles should be 0.8mm and their length 13mm.

3.3 Influence of wire tension

Before introducing the wires into the propellant mix for the purpose of extruding a wire-embedded propellant grain, it is necessary to apply a fixed amount of linear tension to the wires. There are many ways of doing this, but the one chosen during our experiments is known as the spring contraction pressure method. It is necessary that the tension applied be appropriate to the particular situation. When there is too much tension, the wires are easily broken. When there is too little or no tension, the wires are bent as they are introduced into the grain.

3.4 Influence of the diameter of the wires

The quality of the wire-embedded propellant grain is influenced not only by nature of the propellant mix and the length and diameter of the mold needles, but also by the diameter of the wires. In general, the finer the wires the less likely they are to bend, but if they are too small they will not be intimately mated to the propellant mix. The diameter of the wires and the axial combustion rate are inter-related. It is necessary to choose mold needles on the basis of pre-determined combustion rates and the corresponding wire diameters.

3.5 Influence of mold length

There is a relationship between the condition of the wires embedded in the grain and the length of the mold. The longer the formation stage of the mold, the more likely the wires will bend. This is because of the tendency of the mix to concentrate in the center of the radius of flow and the pressure applied by relatively old mix on newer mix as it enters the mold. In addition, increasing the length of the formation stage of the mold increases the amount of force necessary to make the wires become mated to the mix. At the same time, the firmly mated wires experience pressure from newer mix as it enters the mold and are bent as they conform to changes in the flow of the mix. Therefore, in addition to ensuring that the wires are firmly mated to the mix as it flows into the mold, it is necessary to choose a mold with a short formation stage. When using SDP-10 propellant mix the angle of the mold's contraction stage cone should be 5-10 degrees and the ratio between the mold's formation stage and its diameter should be $L/D = 4 \sim 6$.

3.7 Influence of the processed propellant mix

The nature of the processed propellant mix has a direct influence on the particular transformations undergone by the mix during its flow throughout the mold. In addition, the nature of the processed mix influences the manner in which the embedded wires undergo stress during molding and the distribution of the wires within the mix itself. If the components of the processed mix are not combined with an even consistency, then the forces exerted on the embedded wires during molding will not be consistent and the wires will consequently be easily distorted. At the same time, it is necessary to choose the most appropriate ratio of constituents for the mix itself. If the mix is too firm, its flow characteristics will be poor and it will be difficult to insert the wires correctly. On the other hand, if the mix is too soft, then the mix and wires will flow together within the mold and become distorted.

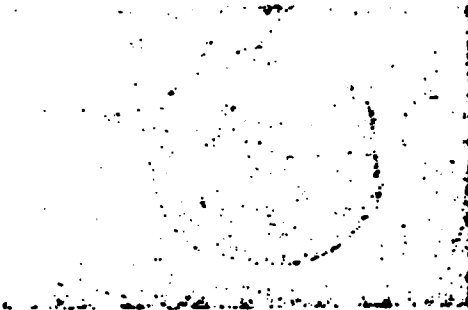


Diagram 3: Photograph of an end-surface combustion propellant grain with six embedded wires after interruption of combustion.

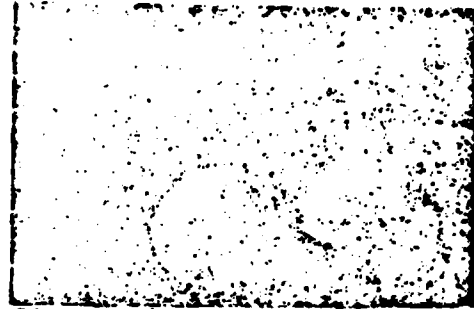


Diagram 4: The arrangement of the end-surface combustion propellant grain with six embedded wires within the 50mm diameter motor.

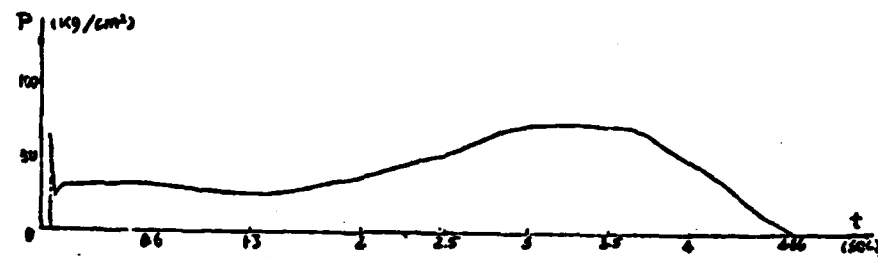


Diagram 5: Power-time curve of the firing of the end-surface combustion propellant grain with six embedded wires (with 15mm of surface coating excised).

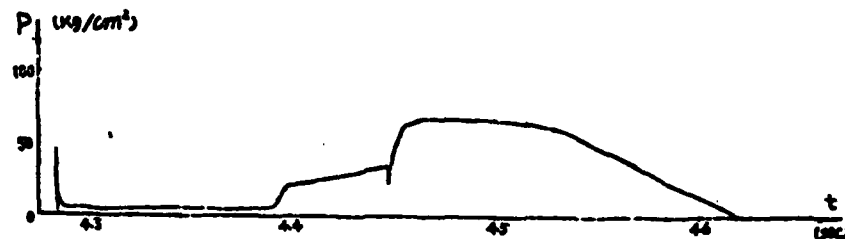


Diagram 6: Power-time curve of the firing of the end-surface combustion propellant grain with six embedded wires.

3.8 Influences arising during fabrication

Temperature during the process of screw extrusion and molding fabrication has a direct influence on the flow characteristics of the propellant mix within the screw extruder and the mold. Because of this very strict conditions must be maintained so as to achieve consistency of fabrication.

The temperature of the screw extruder body and screw lever are extremely important in the process of extruding propellant grains embedded with continuous wires. By maintaining an appropriate temperature differential between these two components, it is possible to minimize overall changes in temperature during fabrication. The propellant mix will flow smoothly and evenly if it is possible during extrusion to maintain it in one or two adhesion areas within the main body of the screw extruder.

It is preferable to maintain the mix at a single temperature. If this is not possible, the inconsistency of transformation of the mix during the process of molding will make it impossible to avoid distortion of the wires. The optimum conditions for SDP-10 propellant mix are as follows:

main body of the extruder:	70 C
screw lever:	82 C
mold:	82-83 C
cone:	82-83 C
propellant mix:	78-80 C

We believe that the provision of adequate temperature control during fabrication has a favorable impact on the flow characteristics of the propellant mix within the mold. If the temperature of the mix is marginally higher than that of the extrusion apparatus then the friction between the propellant mix and the walls of the mold is lessened and the differences in the flow rate of the mix at every point in the cross section are similarly reduced. Because of this it is possible to accomplish extrusions in which the wires are inserted without distortion.

4. Experimental results and analysis

Experiments were undertaken on the extrusion of propellant grains 45mm in diameter, with 6 inserted silver wires, composed of SDP-10 propellant mix, and formed by use of an 80mm diameter screw extruder. Through these experiments, we were able to investigate the most favorable fabrication conditions, mold configuration, length of mold needles, and pre-insertion tension to be applied to the wires. Examination by x-ray photography has been used to detect distortion of the wires within the propellant grain, and repetitions of the experiments have shown the results thereof to be unusually good.

The grains, which were embedded with pre-selected wires, were installed in a 50mm diameter rocket motor and ignited at the 4.4mm diameter throat. As a result, we confirmed that combustion was extremely steady (see diagrams 3 and 4). Examples of p-t (power-time) curves are shown in diagrams 5 and 6.

Experimental conditions are indicated in diagram 1. In the combustion tests, we first sought initial results in the problem of combustion surface area through the use of different configurations of propellant. One such

1 並び	2 モーター			3 火 薬			4 点 火 薬		9 備 考
	D _K	d _K	点火室径	火薬の番号	D	L	7 タイプ	8 重 量	
1	50	4.30	20	1	45.50	116.10	2 $\frac{1}{2}$ + Mg	1.2/0.8	端面に二つの溝付 9a
2	50	4.50	60	7	45.50	118.50	2 $\frac{1}{2}$	5/0	端面に五つの溝付 9b
3	50	4.50	3	4	45.50	106.20	2 $\frac{1}{2}$	2.5/0	端面に二つの溝付 9c
4	50	4.50	3	6	45.50	106.60	2 $\frac{1}{2}$	3.0/0	端面に二つの溝付, 15mmの側面のコーティングを削る 9d
5	50	4.20	3	2	45.50	116.90	2 $\frac{1}{2}$ + Mg	3.0/0.5	端面に二つの溝付, 10mmの側面のコーティングを削る 9e
6	50	4.40	3	5	45.50	112.30	2 $\frac{1}{2}$	3.0/0	端面に二つの溝付, 15mmの側面のコーティングを削る 9f
7	50	4.40	0	3	45.50	115.60	2 $\frac{1}{2}$	3.0/0	端面に二つの溝付, 15mmの側面のコーティングを削る 9g

Table 1: Experimental conditions of the rocket motor.

- Item 1: Number
Item 2: Motor
Item 3: Propellant
Item 4: Ignition material
Item 5: Ignition chamber
Item 6: Propellant number
Item 7: Type
Item 8: Weight
Item 9: Notes
9a: two end-surface grooves
9b: five end-surface grooves
9c: two end-surface grooves
9d: two end-surface grooves, 15mm of surface coating excised
9e: two end-surface grooves, 10mm of surface coating excised
9f: two end-surface grooves, 15mm of surface coating excised
9g: two end-surface grooves, 15mm of surface coating excised

result was that when the propellant grain embedded with continuous wires was fired within the motor, and the initial combustion surface was circular, there were three power stages, as shown in diagram 6. These were the initial stage, steady thrust stage, and final stage. Another result was the p-t curve when the initial combustion surface area was circular and there occurred a round column surface of 15mm in length. In this case, as indicated in diagram 5, after excising 15mm of the surface coating the ignition point of the propellant developed quickly to the steady thrust stage, making this a completely effective technique. Through a great number of other experiments, it was confirmed that when the experimental results were the same, then the recorded configurations of the p-t curve were almost identical.

Within a range of 104-208 kg/cm² of the SDP-10 propellant used in these experiments, we established that there is a relationship between the combustion rate and pressure rating of $r = 0.3665 p^{0.7084}$ (1). We also established that there is a relationship of $P_{np} = 2.9382 \times 10^{-9} K_N^{3.43}$ (2) between the steady thrust power and K_N (the ratio between the combustion surface area and the throat surface area).

Next, using the motor's combustion data, we sought to determine the factor by which the combustion surface area was increased in the 45mm grain with six embedded wires. The experimental data for this motor was as follows: diameter of the throat or $d_K = 4.4$ mm; outer diameter of the grain or $D = 45.5$ mm; and at end surface combustion or $K_N = 106.9$ the greatest thrust or $P_{max} = 120$ kg/cm². Out of the p-t curves for these wire-embedded propellant motors, the greatest thrust that achieved continuous combustion was that of the stable combustion stage of type (2). (See the accompanying chart.)

$$K_N = 3.872 \sqrt{\frac{120}{2.9382 \times 10^{-9}}} = 550.14$$

$$\text{greatest ratio of combustion surface } AS = \frac{550.14}{106.9} = 5.14$$

In other words, according to the calculation above the factor by which the combustion surface of the wire-embedded propellant grains was increased is 5.14. If the experimental conditions of the rocket motor remain the same, the ratio of increase in speed of combustion is identical. This indicates the acceptability of the qualities (including the reproducibility thereof) of the wire-embedded propellant grains produced by the screw extrusion process. The ratio of increase in the combustion surface is related to the type of wire used and the combustion speed of the propellant matrix. This is because combustion takes place within the wire-embedded propellant grain at right angles to the propellant's combustion surface. If the speed of combustion following the wires is expressed as r_f and the propellant's combustion speed is r , because r_f is greater than r the result is a cone with the wires at the axial center.

$$\sin \theta = \frac{r \cdot dt}{r_f \cdot dt} = \frac{r}{r_f} \quad (3)$$

If the relationship between the speed of combustion along the wires r_f and the pressure within the combustion chamber P is expressed in terms of relative ratings, that is, $r_f = a_f P^{n_f}$, then the propellant's speed of combustion $r = a P^n$. Based on the equation $\sin \theta = \frac{a}{a_f} \cdot P^{n-n_f}$, it is known that there is a relationship between the cone's angle θ , the pressure rating of the propellant n , and the pressure rating n_f of the speed of combustion

along the wires r_f . That is, changes in pressure P cause changes in θ . The range of change in θ is limited by the values of n and n_f . Therefore, when seeking a certain necessary ratio of increase in combustion surface area it is possible to seek $\sin \theta$ from the formula $\sin \theta = 1/S$

Once the wire-embedded propellant matrix is decided upon, the values $r = aP_n$ are known accordingly. Further, it is also possible to find the value of r_f through motor type (3). In addition, it should be possible to extrude propellant grains embedded with continuous wires that would fit the motor specifications used in this report by selecting a different type of metal wires (or a different surface coating).

5. Conclusion

It is possible to extrude rocket propellant grains embedded with continuous metal wires by a screw extrusion process developed during the course of this research. The combustion characteristics of such grains are smooth and regular, and it is thus possible to obtain end-point combustion ammunition that will perform repeatedly as expected.

We have undertaken experiments in the production methods of 45mm diameter grains by use of a technique by which grains embedded with continuous metal wires were fabricated by use of a screw extruder. We feel that future experiments should study increases in the scale of production techniques and the manner of combustion of wire-embedded propellant grains. It will also be necessary to investigate different propellant matrices, wire materials, diameters, and coatings, and other factors. (Illegible)

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